CONF-860931--13

EXPERIENCE WITH EBR-II DRIVER FUEL*

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DE87 004997

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Paper to be Presented

at

International Conference on Reliable Fuels for Liquid Metal Reactors

Tucson, Arizona

September 7-11, 1986

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* Work Supported by the U.S. Department of Energy Reactor Systems, Development, and Technology, Under Contract W-31-109-ENG-38

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ABSTRACT

The exceptional performance of Experimental Breeder Reactor-II (EBR-II) metallic driver fuel has been demonstrated by the irradiation of a large number of elements under steady-state, transient overpower, and loss-of-flow conditions. High burnup with high reliability has been achieved by a close coupling of element design and materials selection. Quantification of reliability has allowed full utilization of element lifetime. Improved design and duct materials currently under test are expected to increase the burnup from 8 to 14 at.%.

I. INTRODUCTION

EBR-II has operated successfully for over twenty-two years. During that period the driver fuel has been evolving for two reasons. First, high burnup and reliable performance are necessary for effective application and economic operation of the reactor. Second, it is believed that metallic fuels are a viable option for innovative LMR's. For these reasons, the design of the driver fuel has been successively altered to achieve improved performance.

The early EBR-II driver-fuel design (Mark-IA) allowed only a 17 percent volume increase of the fuel before fuel cladding contact.[1] The fission gas was retained in the fuel and although the cladding offered some restraint to fuel swelling, the cladding would eventually breach at a low burnup when the available cladding ductility was exceeded.

Parallel experimental irradiations of metal fuels were being carried out in the ANL-CP-5 reactor.[2] These irradiations showed that when swelling from fission-gas bubble growth was allowed to exceed ~25 percent, the larger gas bubbles began to interconnect among themselves and with the fuel surface. Most of the fission gas was released from the fuel if it was permitted to swell more than 30 percent. It was reasoned that the fuel element would exhibit higher burnup capability if the designs permitted interconnected porosity with consequent gas release to occur before the fuel contacted the cladding. Fuel with interconnected porosity was thought to be relatively weak and it should, therefore, be easily restrained by the cladding. The porosity would also be available to accommodate the inexorable swelling from solid fission products.

The EBR-II Mark-II fuel element was designed to take advantage of the phenomenon of interconnected porosity. The smear density of the fuel was reduced to 75 percent which allowed 33 percent volume swelling of the fuel before fuel-cladding contact. This magnitude of swelling was well beyond the extent required to produce interconnected porosity and gas release. The gas plenum was designed with sufficient volume to keep the plenum pressure, due to the released gas, reasonably low over the life of the element.

The full benefit of the improved driver fuel came with the development of a means to establish the optimum burnup limit for the fuel. Early methods utilized a "bootstrapping" technique whereby if lead subassemblies performed adequately, then the remainder of the core would be allowed to achieve a burnup near that of the examined lead subassemblies. The technique was deficient in many respects, particularly the expense of examining the lead subassemblies at a given burnup increment and the uncertainty as to whether enough lead subassemblies had been examined to justify an increase in burnup for the entire core.

A disciplined method for core qualification evolved at EBR-II that serves as a benchmark for core qualifications.[3] A small number of subassemblies containing xenon-tagged elements are intentionally run to cladding breach. The location of breach is determined through postirradiation examination and this information is further utilized for safety analyses. The burnups at breach for these subassemblies are then analyzed with Weibull statistical methods to give a quantitative assessment of the likelihood of breach, at any given burnup in an entire core loading of fuel.

II. ELEMENT DESIGN AND FABRICATION

The EBR-II driver-fuel-element has been subject to several design changes. The important design features of the element types are compared in Table I and Fig. 1. With the small plenum of the Mark-I design, it was calculated that for

Table I. Design features of the Mark I, Mark-IA, Mark-II and Mark-IIA Driver-fuel elements

	Mark I	Mark-IA	Mark-II	MarK-IIA
Fuel Alloy, wt percent	U-5 Fs	U-5 Fs	U-5 Fs	U-5 Fs
Enrichment, (at. percent ^{235}U)	48.4	52.5	67.0	67.0
Fuel Pin Length, mm	361	343	343	343
Fuel Pin Diameter, mm	3.65	3.65	3.30	3.30
Fuel Volume, 10^{-6} m^3	3.8	3.6	2.9	2.9
Fuel Smear Density, percent	85	85	75	75
Fuel/Clad Radial Gap, mm	0.152	0.152	0.254	0.254
Cladding Wall Thickness, mm	0.23	0.23	0.30	0.30
Cladding, o.d., mm	4.42	4.42	4.42	4.42
Cladding Material	304L(SA)	304L(SA)	316 (SA)[1]	316 (SA)
Element Length, mm	460	460	612	635
Plenum Volume,[2] 10^{-6} m^3	0.50	0.67	2.41	2.94
Sodium Level, mm	16.5	16.5	27	6.4
Restrainer	Internal	Internal	Chisel-shaped Indentation	Spherical Indentation

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[1] Solution-annealed Type 316 stainless steel is presently the reference cladding material. Some experimental Mark-II elements were clad with solution-annealed Type 304L stainless steel.

[2] At room temperature.

fuel-swelling volume changes in excess of 8 percent, the pressure inside the element would begin to approach the postirradiated burst strength of the cladding.[4] Since an 8 percent volume-swelling change of the Mark-I fuel was attained at a fuel burnup of 1.2 at. percent, this burnup was established as the initial limit. Then it was reasoned that if the gas-plenum volume could be increased relative to a given fuel-volume change due to swelling, the internal pressure would be less and the burnup limit could be extended. The Mark-IA was therefore designed with a shorter pin to increase the plenum volume and the ^{235}U enrichment was increased to compensate for the shorter pin. However, at the same time the design change was instituted, the fuel used for the Mark-IA exhibited a higher swelling rate, and this led to a plenum-volume decrease that almost exactly canceled the potential benefit of the design change.

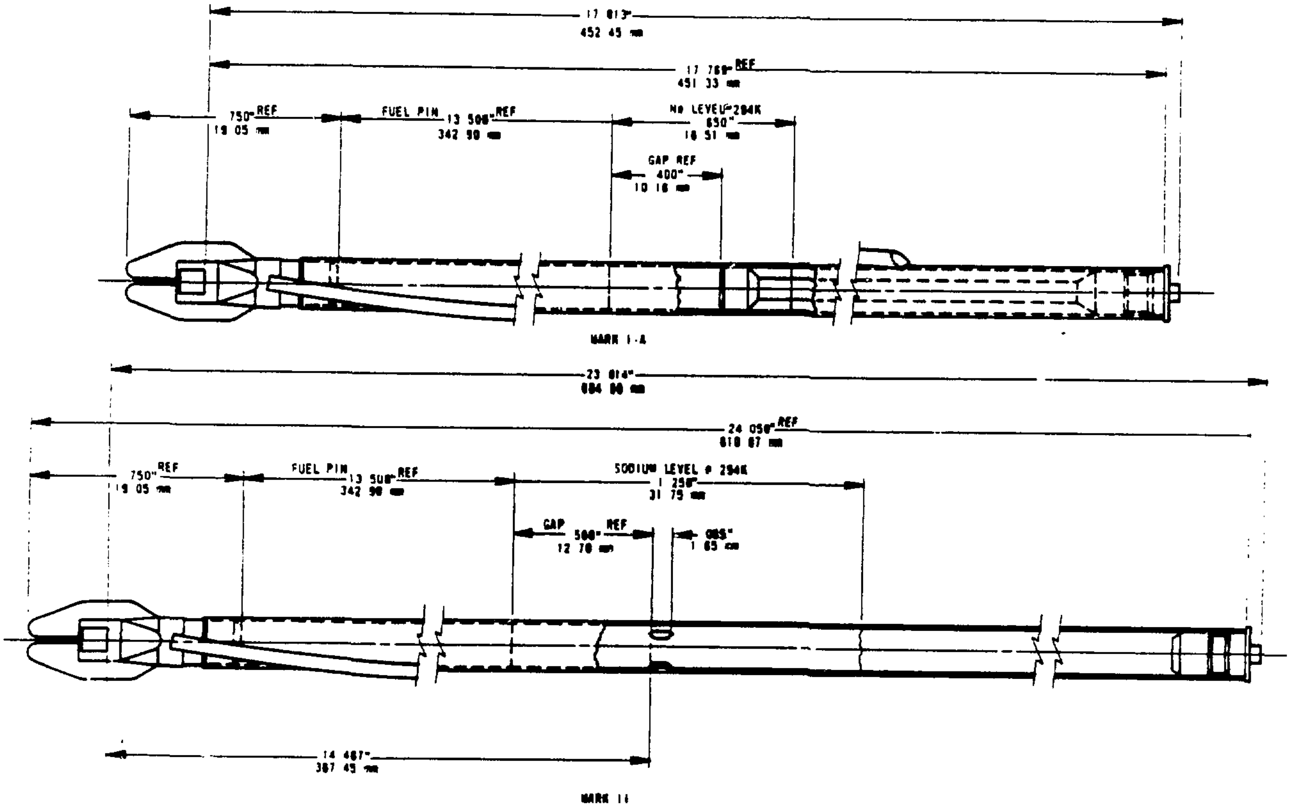

Fig. 1. EBR-II Driver-fuel Designs

The Mark-II design was instituted to take advantage of the interconnected-porosity phenomenon, which has been described earlier, so that by the time of fuel-cladding contact, interconnected porosity had occurred. Several design variations that included the type of fuel-pin restrainer, the magnitude of the plenum volume, and the cladding alloy were explored prior to the choice of the reference Mark-II design.[3] The important design changes of the Mark-II compared to the Mark-IA were the lower smear density, the larger plenum volume, the thicker cladding, and the cladding material. The Mark-IIA design evolved to alleviate the premature breach caused by the chisel-shaped indentation and to increase the plenum volume by lengthening the element 25 mm and lowering the bond sodium level.

III. EBR-II DRIVER-FUEL PERFORMANCE

The current exceptional performance of EBR-II driver fuel has been due to success with both design and materials.

The element design, as described earlier, was modified to take advantage of the observed fuel swelling and subsequent fission-gas release in metallic fuels. The stresses within the cladding were decreased by increasing the plenum volume and the cladding thickness. Replacement of the Type 304L cladding material with Type 316 material increased the strength, decreased the irradiation swelling rates, and decreased the fuel-cladding chemical interactions rates.

At present, the Mark-IA design is limited to 3 at. percent burnup at a peak cladding temperature of 550°C, and the Mark-II design is limited to 10 at. percent at 590°C peak cladding temperature. Since the dimple restrainer of the Mark-II element has been the preferred site for end-of-life breaches, the alternative design of the Mark-IIA is expected to eliminate breach in the dimple region, significantly increasing the lifetime. Mark-IA elements are no longer used.

The key to this success and to development of its future potential lies in an understanding of the proven consistent behavior of the EBR-II driver fuel. The significant materials-related, steady-state performance characteristics of metallic EBR-II driver fuel are related to fuel swelling, fission-product distribution, fuel-cladding chemical interaction, diameter increase, cladding breach, and resultant lifetime.

Fuel Swelling. Fuel deformation is due primarily to retained fission gas and solid-fission-product accumulation within the matrix. Early irradiations indicated that the swelling rate of uranium-5 wt percent fissium was reduced with increased minor amounts of impurities, silicon in particular.[5] Although the rate determined the exposure at which the fuel contacted the cladding, the significant issue was whether the fuel smear density was sufficiently low to allow release of fission gas via interconnected porosity. In a Mark-IA fuel element with a smear density of 85 percent, the fuel contacted the cladding over the full extent of the fuel column by 1.8 at. percent burnup.[5] Within an additional 1.5 at. percent burnup, the loading on the cladding by the deforming fuel in addition to the high plenum pressure caused breach in the fuel-column region.[1] In contrast, in the Mark-II fuel element with a smear density of 75 percent, the fuel came into full contact with the cladding by 3.2 at. percent burnup and the element proceeded an additional 7 at. percent burnup before breach occurred in the dimple restrainer at the top of the fuel column.[6]

The fuel swelled at equivalent rates for equal temperatures in both designs, but the low-smear-density design allowed dynamic and repeated swelling of the matrix fuel into the continually developing and decaying interconnected porosity (Fig. 2). This dynamic process of closed fission-gas porosity growing and interconnecting and then being eliminated by additional fuel swelling never occurred in the Mark-IA element, whereas several complete cycles were achieved in the Mark-II element.

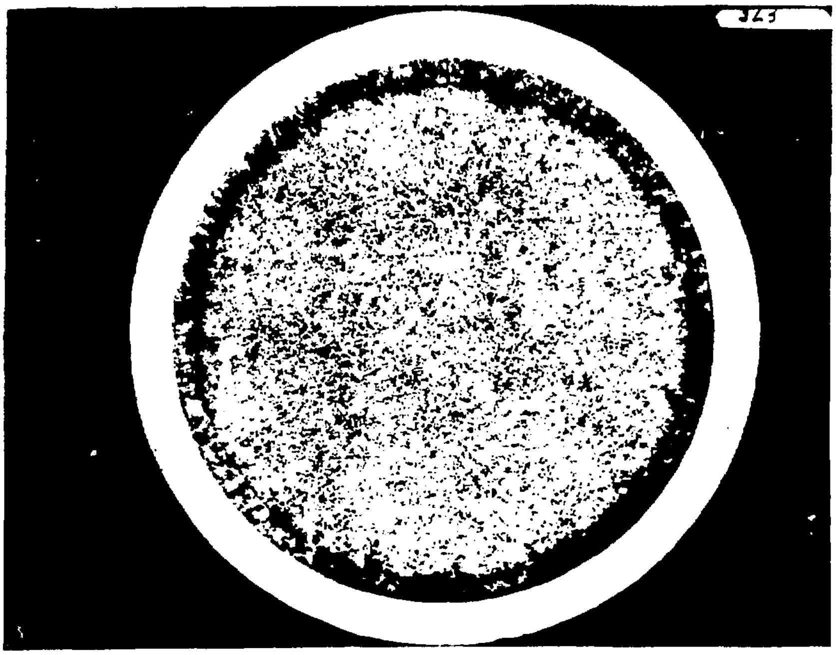

Fig. 2. Fuel Structure of Mark-II Driver-Fuel Element Near Top of Fuel Column (~575°C Peak Cladding Temperature at 7.9 at.% Burnup

Fig. 3. Fuel-cladding Chemical Interaction Near Core Midplane (~480°C Peak Cladding Temperature) in a Mark-II Fuel Element at 10.3 at.% Burnup

The fuel deformation was primarily radial and was readily restrained when interconnected porosity was allowed. Axial deformation also could be restrained, but apparently was self-limiting.[7] Axial restraint is not necessary to limit fuel-pin liftoff. (Liftoff is a term describing the observation of fuel being displaced above the lower fuel-pin support).

Fuel-Cladding Chemical Interaction (FCCI). Primarily, nickel diffused from the Mark-II Type 316 stainless steel cladding into the fuel, leaving a nickel-depleted zone in the cladding and an enriched zone in the fuel.[7,8] Only limited diffusion of the uranium into the cladding occurred. The interaction zone exhibited uniform fronts at both the fuel and the cladding interfaces (Fig. 3). Only 5 percent of the cladding wall thickness was consumed at more than 10 at. percent burnup at peak cladding temperatures of 590°C. The penetration into the fuel was found to be 3-10 times greater than penetration into the cladding.

Because of the limited exposure of the Mark-IA elements, no FCCI was observed. Irradiation of Mark-II elements clad with Type 304L stainless steel, however, indicated that interpenetration was much greater than that observed with 316 stainless steel.[7]

Diameter Increase. The peak diameter increases observed for the two element designs with increasing burnup were significantly different. As shown in Fig. 4, the increase at equivalent burnup for the 304L-clad Mark-IA elements was greater than observed for Mark-II elements clad with 304L stainless steel, and much greater than that exhibited by the reference-design 316 stainless steel cladding.

The peak diameters were observed between the midplane and the top of the fuel column, where the convolution of flux and temperature was maximum. The increases in diameter resulted from irradiation swelling and creep. About 50% of the peak diameter increase of the Mark-IA elements was due to swelling as measured by immersion-density techniques. The swelling component typically comprises 67 to 85% of the total increase in a Mark-II element.

Interaction between each element and its spacer wire developed with increasing burnup. Since the temperature of the spacer wire was below that of the cladding, the swelling rate of the wire was less also. The spacer wire became tighter and tighter with increasing burnup. Elements examined after 11.5 at. percent burnup exhibited a helical aspect due to constraint by the wire. The diametral profiles of the Mark-II elements show periodic ovality due to element/spacer-wire interaction at the elevations of contact between the element, its spacer wire, and adjacent spacer wires. In general, the orientation of the ovality in cross section has no correspondence with the spacer wire until the diameter increase of the elements in the bundle was sufficient to cause interaction. Above 1% diameter increase, the interaction caused the ovality to be oriented in relationship with the spacer-wire position.

Cladding Breach and Element Lifetime. Breach of Mark-IA cladding has always occurred in the fuel-column region. The defects were intergranular in nature and originated on the outer cladding surface. Olson[1] has described the breach characteristics and statistically determined that the threshold for breach was 3 at. percent burnup for nominal 550°C beginning-of-life peak cladding temperatures. Subsequent irradiations have shown that the lifetime was decreased to 2.7 at. percent burnup for slightly higher operating temperatures.

Breach of Mark-II driver-fuel elements has been at substantially higher burnups. Weibull statistical analysis of lifetime based on measured lifetimes obtained from run-to-cladding-breach subassemblies has permitted an increase in exposure limit from less than 1 to 8 at. percent burnup. Early information was obtained from experimental elements irradiated in capsules to breach. The elements were clad with 304L stainless steel and were either 610 or 660 mm in length; they also incorporated several other new design features.[7] The additional plenum length of 50 mm provided an additional 1.5 at. percent burnup of life over the minimum life of 8.9 at. percent burnup. All the breaches occurred in the fuel-column region.

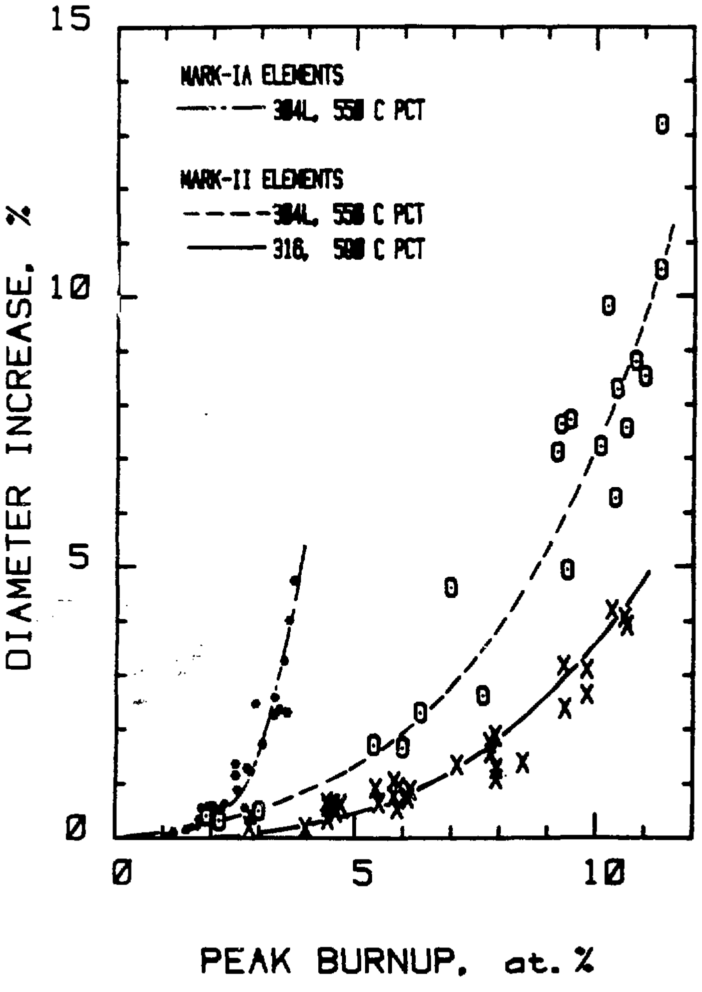

Fig. 4. Diameter Increase of Mark-II Fuel Elements with Increasing Burnup

Reference-design Mark-II elements clad with 316 stainless steel have consistently breached in the dimple restrainer above 10 at. percent burnup for the elements with the highest peak cladding temperatures in the EBR-II core. Elements operating cooler breach at higher burnups.[6] The defects (Fig. 5) originated on the outer surface, were intergranular and about 3 mm long, and appeared to have resulted from bending of the dimple due to high stresses at the inner cladding surface. Defects have been observed in all the dimples of breached elements as shown in Fig. 6.

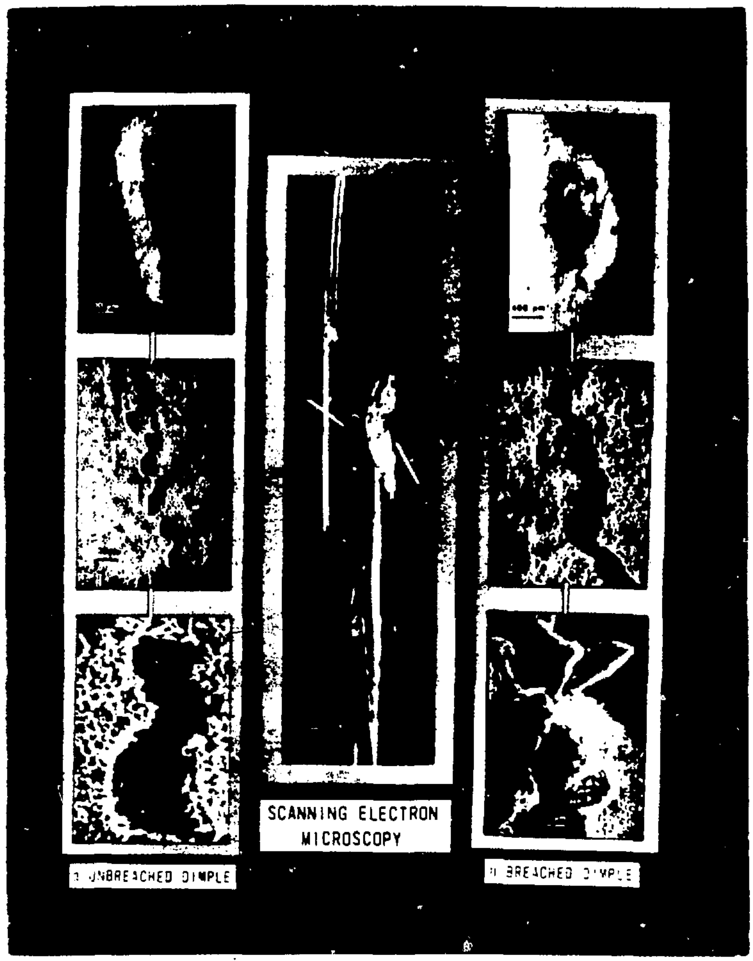

Fig. 5. Scanning-electron Micrographs of the Outer Cladding Surface in the Dimple Region of a Breached Mark-II Fuel Element at 10.7 at.% Burnup

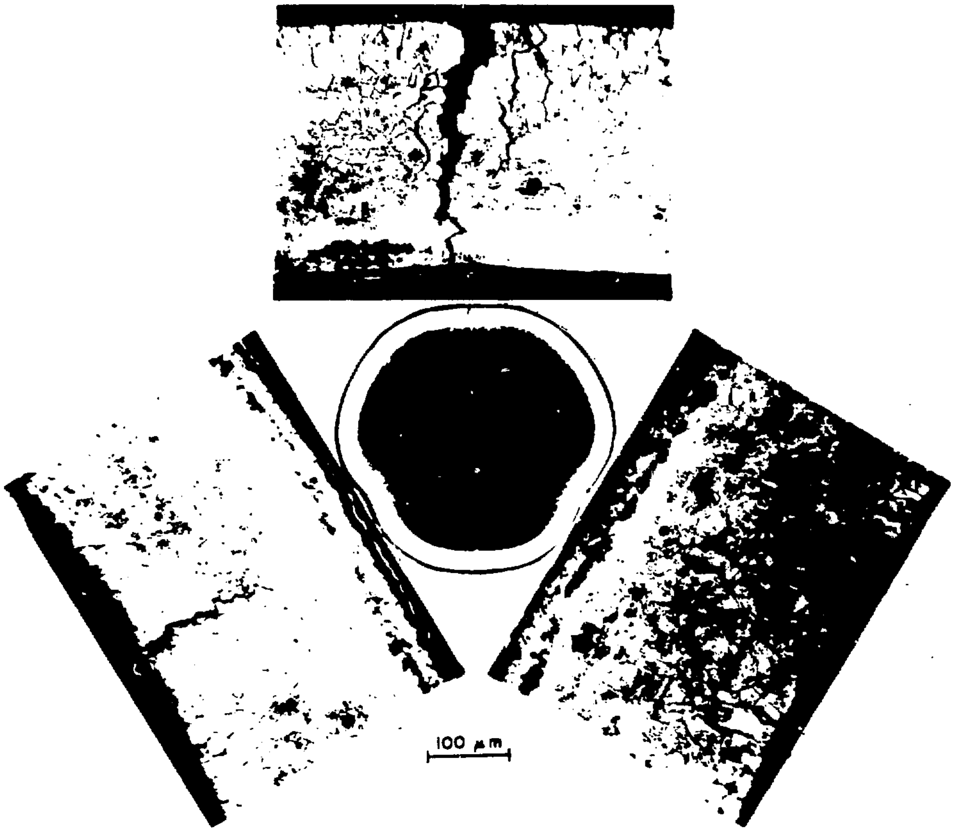

Fig. 6. Optical Micrographs of the Dimple Region in Cross-section Characterizing Breach

Weibull statistical analysis of the dimple breaches has shown that no breaches could be expected below 10 at. percent burnup and that the breach rate was very high once that burnup was surpassed. Several breaches since the early analysis have verified the validity of the lifetime correlation for Mark-II elements exhibiting dimple breach.

Recently, breach was observed between 9 and 12 at. percent burnup in the plenum region of one element each from two subassemblies irradiated at a slightly lower cladding temperature but higher heat rating. One breach was located near the upper spacer-wire-to-tubing weld. The defect was very small and intergranular in nature. Further analysis is expected to determine if the defect was due to interaction between the element and the spacer wire. The defect in the other breached element was too small to detect, even by internal pressurization to 38.6 MPa; but from fission-gas release data, weight measurement, and activity smears of the outer element surface, the position of the defect was limited to the plenum region. Welding defects, etc. have also been found to occasionally cause breach at high burnup. Defect-free elements, however, fail in the restrainer and 18.5% burnup has been achieved in Mark-II elements before breach when cladding temperatures are low (500-520°C).

In addition to RTCB experiments, irradiation of large numbers of driver-fuel elements to high burnup without breach has shown the reliability of the element. Figure 7 graphically illustrates the reliability proven by irradiating the driver fuel to the increased burnup limits of 4.7,6, and 8 at. percent. The RTCB irradiations have defined the region of proven unreliability. A significant margin of reliability exists between the current 8 at. percent burnup limit and the initiation of dimple breach.

The lifetime of Mark-II elements was also decreased by irradiation at higher temperature. Dimple breach has been observed at 9.2 at. percent burnup in an element operated at 615°C peak cladding temperature. A second experimental irradiation at higher temperature surpassed 10 at. percent burnup without breach; sibling elements at normal temperature have breached in the dimple at 11.5 at. percent burnup. The factors controlling metal fuel lifetimes are extensively addressed in a related paper in this conference.[9]

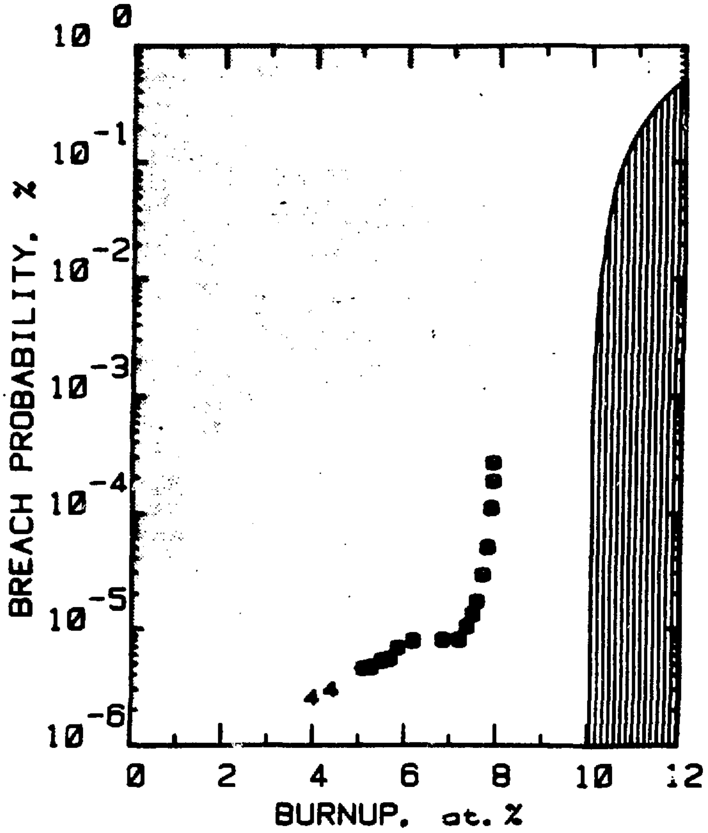

Fig. 7. Quantified Reliability of Mark-II Driver-fuel Elements

Off-Normal Performance. Along with demonstrated highly reliable steady-state performance, metallic fuel has been shown to be extremely tolerant of off-normal events. In the late 1970s and early 1980s, the mission of EBR-II was changed from purely steady-state irradiation to a mission that combined steady-state irradiation with the capability to subject fuel to transient overpower and loss-of-flow events. During the process of learning whether EBR-II would be capable of sustaining multiple transient operations, a capability required for the proposed mission, it was discovered that metallic fuel was extremely tolerant of transient events.

In addition to a number of ex-core and in-core tests on single fuel pins and assemblies, the entire core of EBR-II was subjected to multiple reactivity insertions at rates of up to 10 ¢/s. No cladding breaches occurred either during the transient tests or subsequently during steady-state operations. Postirradiation examination of the fuel revealed no observable degradation such as additional cladding strain or cladding attack. Rather than stressing the cladding during the transient events the fuel flowed into the available open porosity.

An extensive summary of off-normal performance of EBR-II driver fuel is presented in this conference.[10]

Performance Summary. In summary the Mark-IA element performed adequately to end of life. Useful life was limited because the high-smear-density design did not allow significant fission-gas release and because of a very limited plenum volume. Had the design been improved, the life would have been limited by the materials performance of the 304L cladding.

The Mark-II element has performed beyond all expectations because of the low smear density and the fuel-to-plenum ratio of 1.2. The 316 stainless steel cladding material exhibited less swelling, creep, and FCCI. Lifetime was limited by breach in the dimple restrainer at burnups greater than 10 at. percent. The life could be extended by a design change. The high reliability of the Mark-II element has been verified by lead RTCB irradiations and the irradiation of many thousands of elements to high burnup without breach. The Mark-IIA design is expected to achieve very high burnup (> 14 at. percent) before breach.

IV. HARDWARE AND FUEL HANDLING PERFORMANCE

Design Restrictions. The EBR-II subassembly consists of a simple hexagonal duct welded to a lower pole piece which is inserted into the two grid plates of the reactor to provide vertical and lateral support for the assembly. An upper adapter is used simply for fuel handling. Approximately 39 mm above the core centerline, the ducts are dimpled outward so there is a nominal clearance at zero power of approximately 0.05 mm between ducts at this location. A restraint ring is located at the top of the ducts with the nominal assembly clearance of 0.762 mm.

The limitations for fuel handling center about the withdrawal loads during assembly removal and a design limitation of the reactor storage basket. The configuration of the entry into the storage positions limits hex duct diametral growth to one mm. The latter constraint has been the most severe.

Hardware Performance. The concerns with the assembly hardware include element bundle-duct interaction, duct diameter increase and bow, and fuel handling forces.

Element contact with the hexagonal duct initially occurs at elevations periodic with the pitch of the spacer wire. Additional diameter increases of the elements and the spacer wire of each can only be accommodated by bending of the element in the direction opposite the spacer wire until the diameter increase consumes the initial clearance of one spacer-wire diameter. With no increase in the dimensions of the hexagonal duct, the elements can only increase 3.6% in diameter before rearrangement of the elements within the bundle is required.

The driver-fuel subassembly with a nominal hexagonal flat-to-flat outer dimension of 58.2 mm contains 91 elements. Interaction between the elements occurs at a 0.4% diameter increase, based on nominal minimum tolerances. Element bending allows accommodation of diameter increases to 3%.

Interaction between the 61 Mark-IA elements in control- and safety-rod subassemblies and the hexagonal subassembly duct with a nominal flat-to-flat outer dimension at 46.6 mm begins at a diameter increase of 0.5%, based on nominal minimum tolerances. At that average diameter increase, the elements along the hexagonal diagonals would just contact each other.

Swelling and creep of the hexagonal duct of the control and safety rod is constrained by a guide ring near the core midplane. However, the driver-fuel hexagonal duct is only constrained by its neighbors. Increases in the driver-fuel duct allow clearance to accommodate additional element diameter increases of 1.8% before the elements and spacer wires must either rearrange within the bundle or begin to stress the duct.

The Mark-II elements have shown element bending about the spacer wire and ovality oriented with the spacer wire but with no ill effects.

Subassemblies of each type have been impregnated with a low-melting eutectic alloy in preparation for transverse sectioning and subsequent analysis of interactions within the whole bundle of elements.

The robust character of the bundle and reliability of the elements are illustrated by the test where a standard driver fuel bundle was reconstituted at 6 at. percent burnup with a fresh low swelling duct of 12% CW 316 stainless steel and then irradiated to 9.4 at.% burnup. That one element was inserted on the grid 180° out of phase and yet survived the irradiation and caused no other problems in the bundle is most significant, Fig. 8.

The current 8 at. percent burnup is based partially on providing a statistical margin to cladding breach, but the limit is largely based on hex duct dilation. The hex ducts have been constructed from solution-annealed 304 (SA 304) stainless steel. Swelling generates flat-to-flat dilations which approach the size limitations of the smallest openings in the EBR-II storage basket when the subassemblies reach a peak fuel burnup of ~ 8 at. percent. Therefore, despite the fact that a very conservative margin to cladding breach is provided by an 8 at. percent burnup, hex duct dilation has limited EBR-II

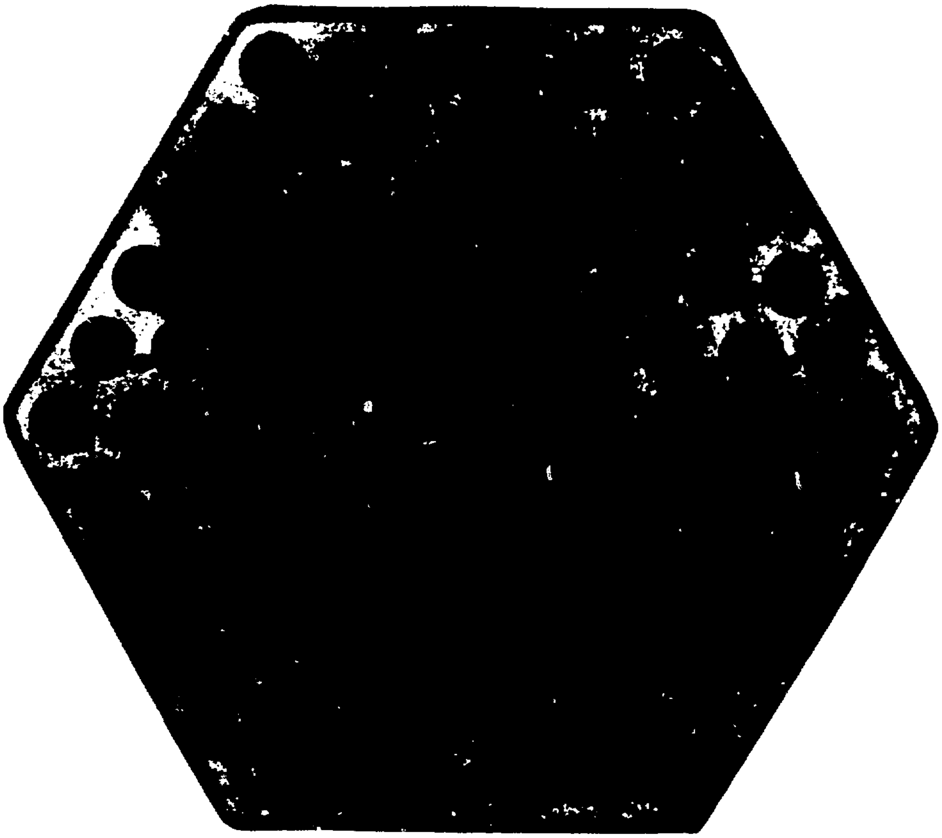

Fig. 8. Cross section of X252 Fuel Bundle at 9.4 at.% Burnup Interaction of Tight Bundle with Reverse-loaded Element

driver fuel to this burnup limit as the subassemblies must fit into the storage basket to allow for decay heat removal and subsequent transfer out of the reactor.

The hex duct dilation data and predictions are shown in Fig. 9. The fast neutron fluence limit for SA 304 is nearly 7 x 10^{22} n/cm^2 which corresponds to ~ 8 at. percent burnup. Also plotted is the equation for 12% cold-worked 316 (12% CW 316) stainless steel hex cans which are now being used in EBR-II. This material allows use of these hex ducts for driver fuel subassemblies to nearly 10 x 10^{22} n/cm^2 (E>01.MEV), or ~ 12 at. percent fuel burnup. Note that the 12% CW 316 data shows that the equation is conservative. Improved fuel element designs are therefore likely to allow for an increased burnup limit for EBR-II driver fuel.

Subassembly bowing has not presented problems concerning driver fuel subassemblies. The temperature and flux gradients (radial) within the core are small and do not cause swelling-induced bow to any great extent.

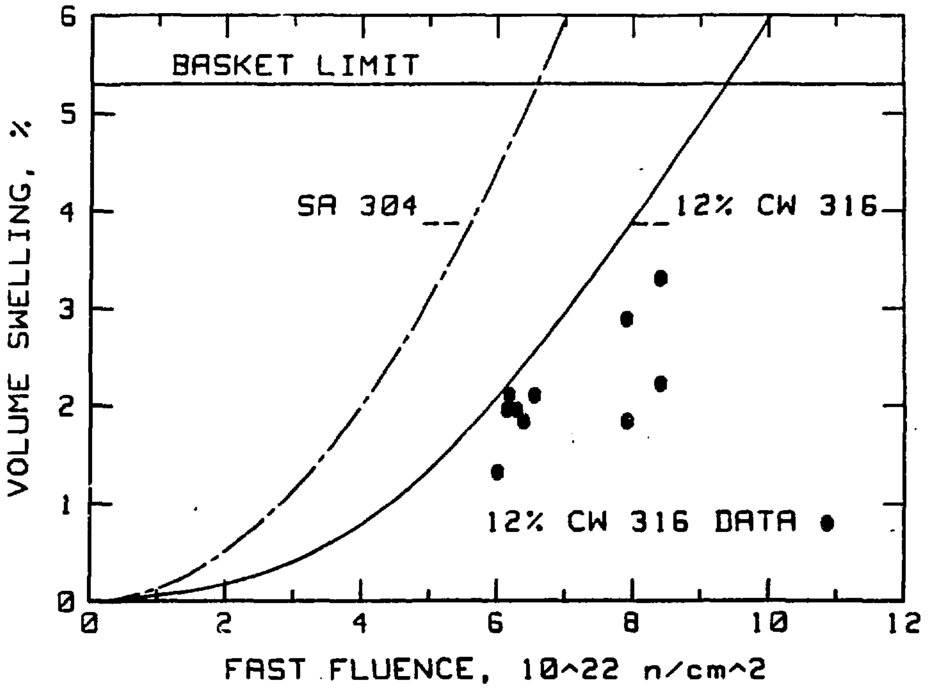

Fig. 9. Measured and Predicted Hex-duct Dilation for the Reference SA-304 and Memer 12% CW-316 Ducts

Fuel handling forces are routinely monitored not only for the driver fuel but also for the reflector and blanket assemblies. The latter have each caused extra fuel handling but no driver assemblies have caused problems. The duct diameter increase limit is more stringent than fuel handling forces caused by bow.

V. CONCLUSIONS

EBR-II driver fuel has demonstrated adequate performance and reliability under both standard and off-normal operating conditions. Improvements in design and materials have steadily increased the lifetime.

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